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A major goal of this investigation is to develop a high-speed laser scanning technique for characterizing the instantaneous topology and vorticity distributions over crossflow planes of a delta wing undergoing defined rolling motion at a given angle of attack. By using new types of image construction techniques, it will be possible to determine the central physics of the three-dimensional flow structure in both the early stages of vortex breakdown, as well as in fully-stalled regions along the wing. In turn, these observations provide a basis for physically interpreting the unsteady loading on the wing. Central to this interpretation are topological representations of the streamline patterns, which provide a quantitative framework for classifying the flow patterns.

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FINAL TECHNICAL REPORT FOR AFOSR GRANT

ADVANCED IMAGING TECHNIQUES FOR FLOWS PAST SWEEPED WINGS

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1. ABSTRACT

A major goal of this investigation is to develop a high-speed laser scanning technique for characterizing the instantaneous topology and vorticity distributions over crossflow planes of a delta wing undergoing defined rolling motion at a given angle of attack. By using new types of image construction techniques, it will be possible to determine the central physics of the three-dimensional flow structure in both the early stages of vortex breakdown, as well as in fully-stalled regions along the wing. In turn, these observations provide a basis for physically interpreting the unsteady loading on the wing. Central to this interpretation are topological representations of the streamline patterns, which provide a quantitative framework for classifying the flow patterns.

2. EXPERIMENTAL SYSTEMS

The central focus of this experimental investigation is to employ image-density particle image velocimetry for characterization of the three-dimensional flow past a delta wing at high angle-of-attack, at finite roll angle, both for static and dynamic situations. Characterization of these complex flows has required design and construction of an integrated experimental system, comprising the rolling delta wing, a scanning laser beam, a diffraction-free image transmission system from the location of the delta wing to the location of the camera exterior to the test section, and a computer-controlled image acquisition system involving an image-shifting mirror, and a 35 mm camera. This entire system is controlled by the laboratory microcomputer.

The rolling delta wing (Figure 1) is modeled after the configuration used in the SARL wind tunnel tests at Wright Patterson Air Force Base. In essence, it has a sweep angle of 65° and a center body of circular cross-section. In our laboratory, this wing is mounted on a stand that allows its roll angle to be controlled by a high resolution motor. Successive static positioning for dynamic rolling of the wing attainable. This entire system can be translated in the water channel to allow positioning with respect to the laser sheet (Figure 2).

The scanning laser sheet (Figure 3) was generated by a beam from a continuous wave, Argon-ion laser having an output of 5 watts maximum. The beam from the laser was transmitted through an arrangement of two lenses, which allowed the focal point to be adjusted at the location of the delta wing in the water channel. After passing through this optical arrangement, the beam impinged upon a rotating, polygonal mirror having 72 facets. This rapidly-scanning laser sheet provided the equivalent of pulsed illumination, but with higher intensity levels and that attainable with a classical, chopped laser beam transmitted through a cylindrical lens. Design and preliminary implementation of a two-axis laser scanning system, whereby two scanning sheets, perpendicular to each other, allow simultaneous, orthogonal views of the flowfield, has been assessed on a preliminary basis.

Crucial is design of a liquid lens system that allowed zero refraction of the rays emanating from the plane of the laser sheet. This was accomplished by use of two, large triangular liquid prisms. These prisms involved hollow Plexiglas attachments having a triangular cross-section, and attached to the exterior of the water channel. They were filled with water; due to the nearly equal indices of refraction of water and Plexiglas, the rays from the laser sheet to the camera lens experienced insignificant refraction.

The image acquisition system involved a rotating (bias) mirror and a 35 mm, motor driven camera. The rotating mirror allowed image shifting, corresponding to a constant displacement of each particle in the laser sheet. Using this approach, all the images recorded on film correspond to unambiguous velocity components. This technique is especially important in assessing regions of vortex breakdown, where reverse flow can occur, and the dynamic range of the particle displacement is particularly large. Both of these limitations can be circumvented by proper employment of the image shifting system.

Post-processing of the acquired images involves determination of the velocity field, then calculation of the distributions of vorticity and the streamline patterns. Software allowing ensemble-averaging, spatial filtering, and other related assessments of the nonstationary flow field have been developed during the course of this program.

3. ACCOMPLISHMENTS/NEW FINDINGS

When the delta wing is subjected to stationary variations in roll angle, the location of vortex breakdown exhibits moderate changes with successive increase in roll angle until a so-called critical state is attained, when relatively large changes in breakdown occur for an incremental change in roll angle. This clear identification of critical states for a rolling delta wing has important implications for a wing undergoing a transient maneuver; substantial alterations in the wing loading are expected to occur at this critical state. It was also observed, however, that the onset of vortex breakdown is, at a given value of roll angle, nonstationary. Streamwise excursions, which can be a substantial percentage of the wing chord, are observed for all values of roll angle. It is hypothesized that the feedback from the downstream wake region of the breakdown, which is highly

nonstationary, may influence the unsteadiness of the onset of breakdown. All of these features have been characterized primarily using dye visualization. In selected cases, cross-sectional views can be obtained using a laser sheet.

Use of the technique of high-image-density particle image velocimetry (PIV) has allowed characterization of the time-dependent topology of the leading-edge vortices over the crossflow plane (Figure 4) and in a plane coincident with the axis of the vortex. Topological concepts, involving critical point theory have allowed identification of crucial critical points in the flow, such as stable and unstable foci, saddle points, and separation and reattachment points. By comparing this topology at successive instants of time with either the ensemble- or time-averaged topology of the flow, the deviation of critical points from their averaged location and form, can be determined. An important finding, for the case of the crossflow topology, is that the basic topological features of the vortex exhibit a systematic and deterministic variation as the crossflow plane is moved successfully to locations upstream of, at, and downstream of vortex breakdown. A crucial element in this topology is the existence or nonexistence of limit cycle streamlines.

The final phase of evaluation of the PIV images will involve two thrusts. The first involves a snapshot technique of proper orthogonal decomposition (POD) in order to characterize the relative energy levels of the most crucial features of the crossflow topology. The second will address space-time reconstruction of the flow patterns that are given in the cross-section of the flow. These features will allow new types of insight into the highly non-stationary leading-edge vortices, especially in regions well downstream of the onset of vortex breakdown, where the wake-like flow produces large excursions in the form and location of the critical points of the crossflow topology.

4. PERSONNEL SUPPORTED

Kimberly Cipolla Ph.D. Candidate

5. PUBLICATIONS

Cipolla, K. and Rockwell, D. 1995 "Flow Structure on a Stalled Delta Wing Subjected to Small-Amplitude Pitching Motions", *AIAA Journal*, Vol. 33, No. 7, pp. 1256-1262.

Cipolla, K. and Rockwell, D. 1995 "Flow Structure Past a Delta Wing Undergoing Harmonic Rolling Oscillation", Abstract JE6, Bulletin of American Physical Society-DFD, Vol. 40, No. 12, p. 2044, November.

Cipolla, K., Ph.D. Dissertation, Lehigh University, Bethlehem, Pennsylvania 18018 (in progress).

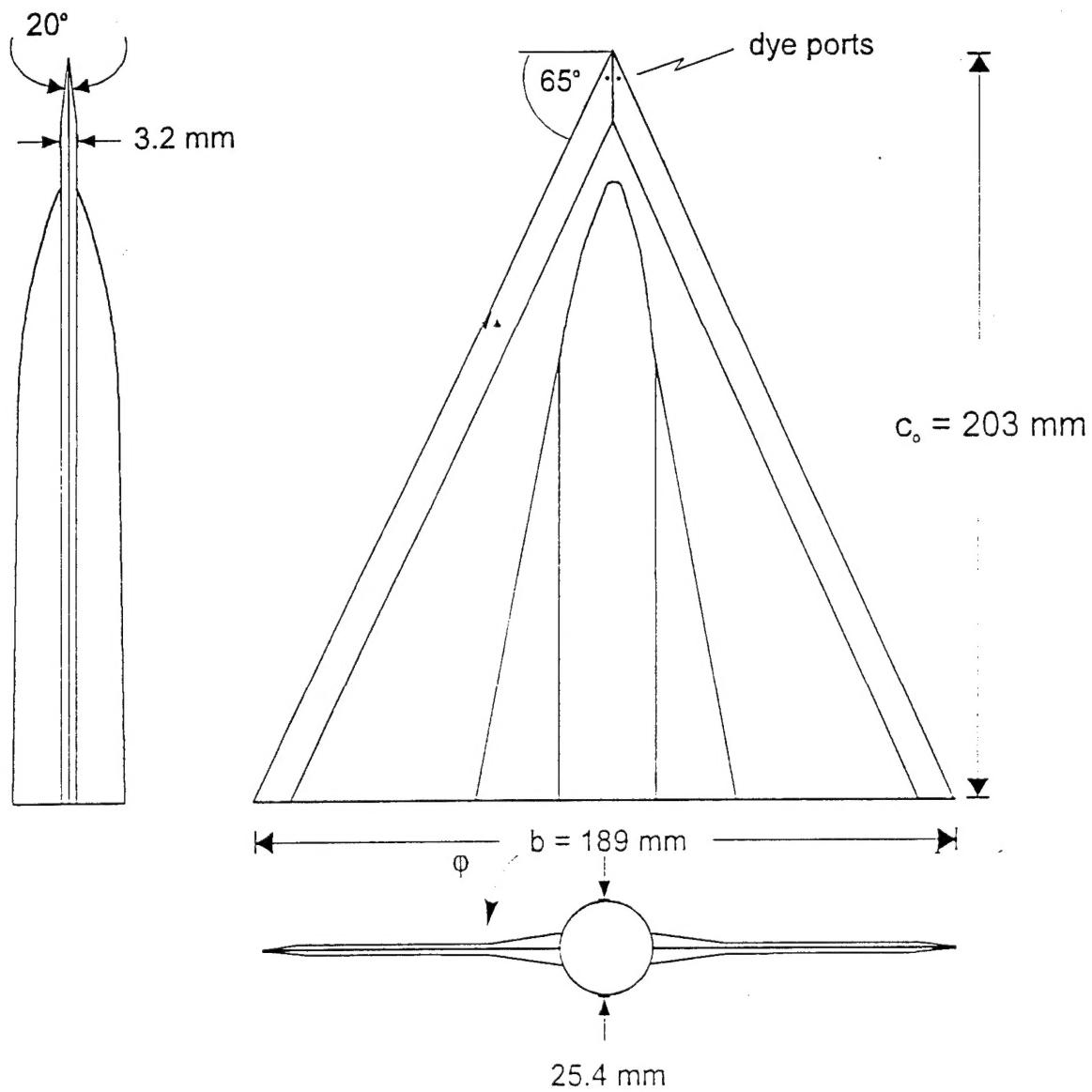
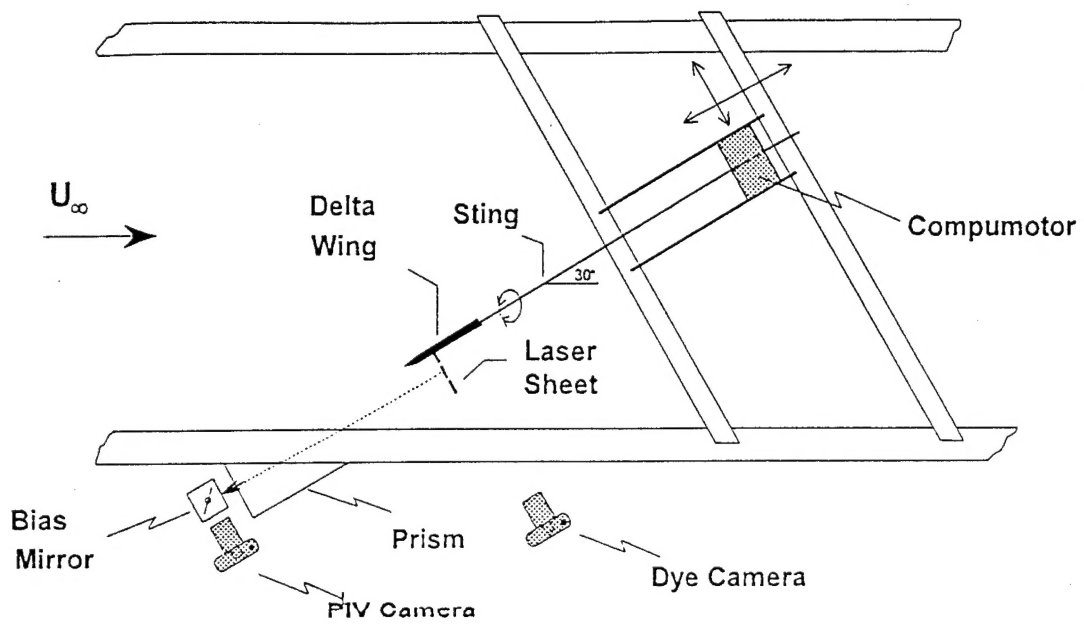
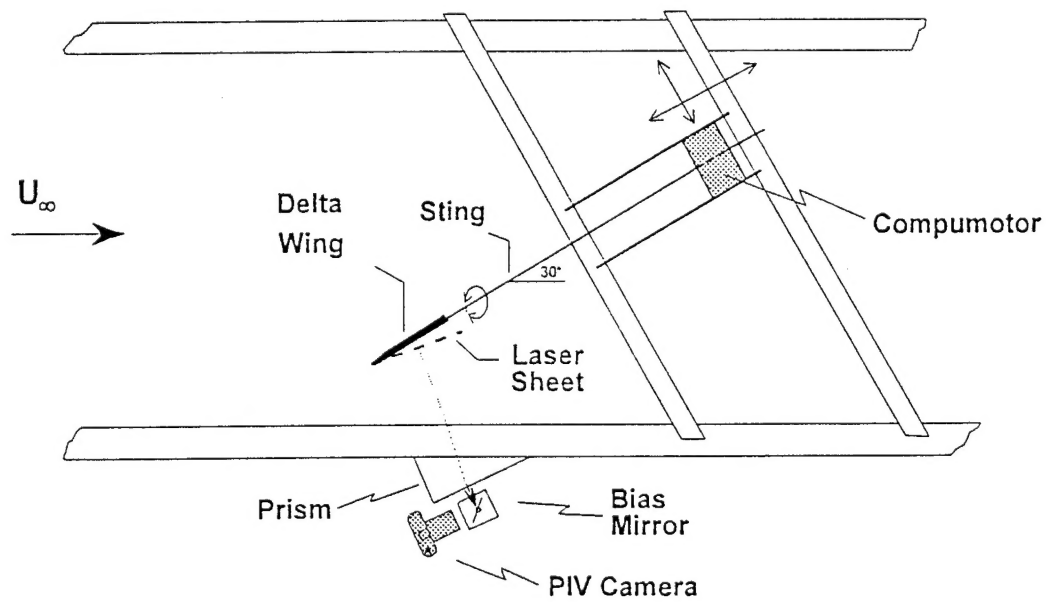


Figure 1: Delta wing geometry.



Crossflow View



Side View

Figure 2: Plan view of experimental setup for crossflow and side view.

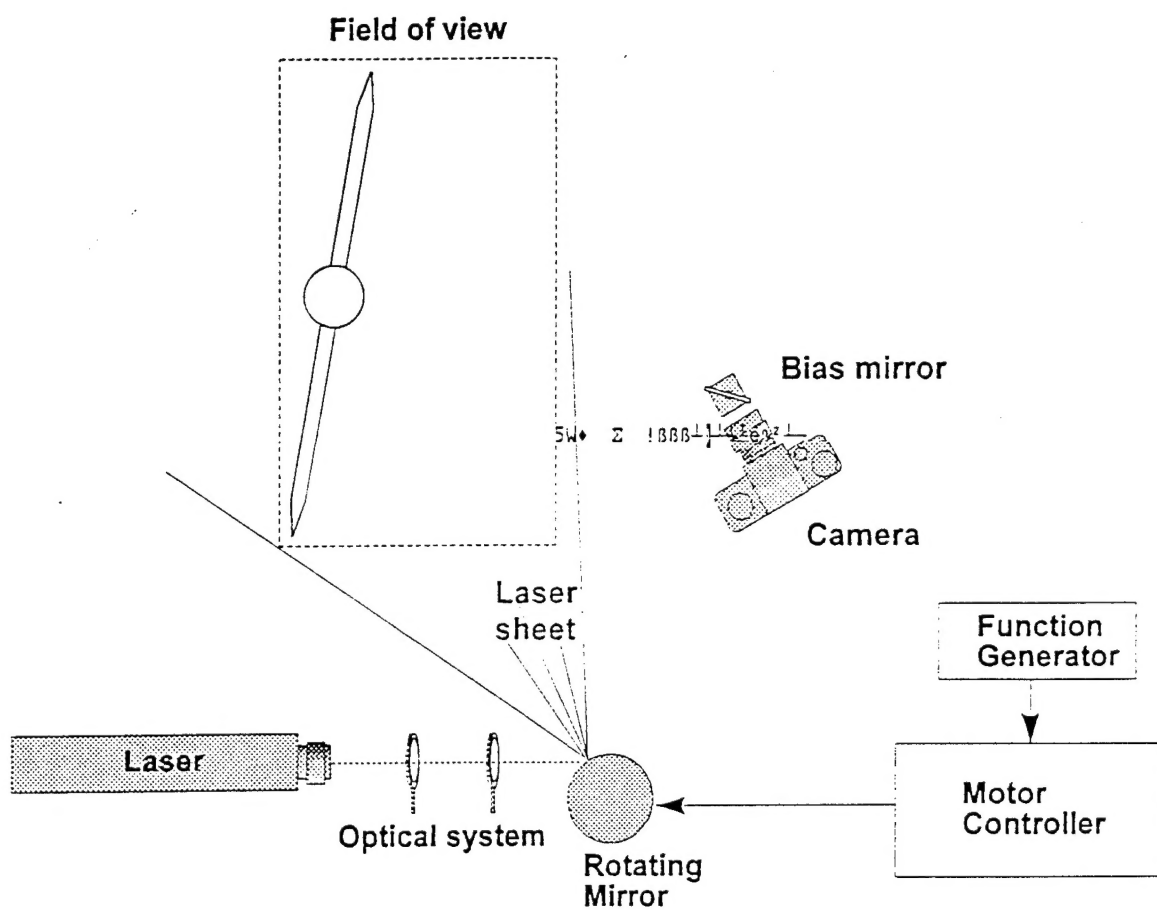


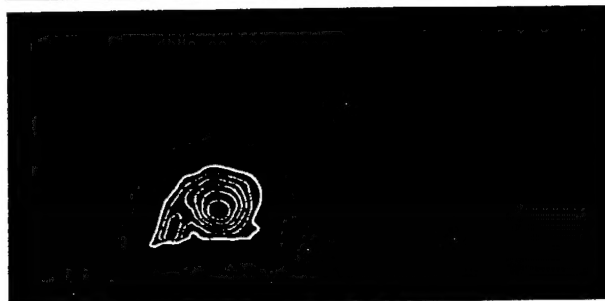
Figure 3: Laser and optical system showing orientation of field of view for a crossflow plane.



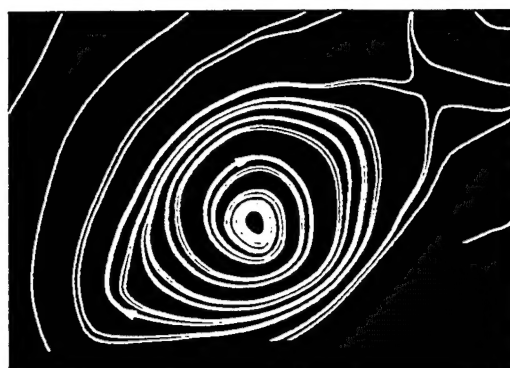
(a) $\phi = -5^\circ$; $x/C = 0.4$



(b) $\phi = -5^\circ$; $x/C = 0.9$



(c) $\phi = -4^\circ$;
 $x/C = 0.4$



(d) $\phi = -5^\circ$;
 $x/C = 0.4$



Figure 4: The structure of the leading-edge vortices along a delta wing is shown in planes perpendicular to the wing centerline at two chordwise locations, x/C . Contours of constant vorticity and streamline patterns are presented in (a) and (b), corresponding to the average of five instantaneous images when the wing is stationary at a roll angle $\phi = -5^\circ$. In (a), the leading-edge vortex on the right-hand side of the wing breaks down at a location upstream of the plane shown, i.e., $x/C < 0.4$, while that on the left-hand side oscillates about $x/C = 0.4$. In (b), the vortices on both sides of the wing have broken down well upstream, as suggested by the distributions of small-scale vorticity. The images of (c) and (d) show instantaneous streamline patterns in a plane located at the same chordwise location, but for different roll angles. An enlargement of the streamline topology clearly shows the abrupt change in the leading-edge vortex from an unstable outward focus to a stable limit cycle. For all cases, the sweep angle of the wing is $\lambda = 65^\circ$ and the angle of attack is $\alpha = 30^\circ$. Flow is towards the reader.